



# Performance of ZrB<sub>2</sub>–Cu composite as an EDM electrode

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## Abstract

The low wear resistance of electrodes like Cu, Cu alloys and graphite is a major problem for electrical discharge machining (EDM) operation. Here an attempt has been made to develop a metal matrix composite (ZrB<sub>2</sub>–Cu) to get an optimum combination of wear resistance, electrical and thermal conductivity. The ZrB<sub>2</sub>–Cu composite have been developed by adding different amounts of Cu and tested as a tool material at different process parameters of EDM during machining of mild steel. The ZrB<sub>2</sub>–40 wt.% Cu composite shows more metal removal rate (MRR) with less tool removal rate (TRR) than commonly used Cu tool. But the diametral overcut and average surface roughness are found to be lesser in case of Cu tool than composite tool. The tools and workpiece surfaces are analyzed by scanning electron microscope (SEM)/EDS and XRD technique.

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## 1. Introduction

The EDM is one of the most promising and widely used non-conventional machining process. The EDM has been a widely accepted standard process for manufacturing dies for forging and extrusion industries. The machining of super alloys, metal matrix composites, advanced ceramics, etc., with close precision and surface finish can be done by EDM satisfactorily where the traditional machining fails [1–3]. The EDM is a thermo-electrical material removal process, in which the tool and the workpiece are connected to two electrodes and separated by a dielectric fluid. The high voltage induces a plasma channel between two conductive electrodes and generates a temperature of ~20,000 °C [4]. At this condition localized evaporation of electrodes takes place in the plasma channel. The material removal is dependent on several EDM parameters such as applied current, pulse duration, gap voltage, frequency of discharge, type of electrode and work material, dielectric flushing condition, etc. The aim of machining process is to obtain higher MRR at reduced TRR with satisfactory surface smoothness. For

close tolerance components, the surface roughness and diametral overcut are very important factors [2].

In EDM, commonly copper and graphite tools are used as electrodes. But high tool wear is the major drawback of these electrodes for prolonged machining. Research is going on to develop a tool material for EDM, which has a high electrical and thermal resistance, high wear resistance and easy fabricability and availability. Many researchers are trying to develop composites material as an EDM tool material by powder metallurgy route. Few composites tool like W–Cu, Cu–WC, Cu–Cr, Cu–ZrB<sub>2</sub>, etc., have been tested for tool material for EDM study [2,4–7]. Singh et al. have observed that performance of W–Cu composite was inferior to Cu tool [2]. But Shunmugam and Philip have improved the wear resistance of machined surface by using WC–Cu composite when the EDM is done under reverse polarity condition [8]. The Cr–Cu composite shows not only higher MRR than Cu but also improved the corrosion resistance of workpiece [5]. Norasetthekul et al. have tried to develop ZrB<sub>2</sub>–Cu composite by infiltration technique and this composite shows higher MRR with lower TRR than Cu and graphite tool [4]. In the present investigation, the EDM performance of ZrB<sub>2</sub>–Cu composite (prepared through liquid phase sintering) tool on mild steel has been carried out at different process parameters. The performance of composite tool is compared with the

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Cu tool. The phase changes in tool and workpiece material during the EDM are also observed.

## 2. Experimental procedure

In the present investigation, the  $\text{ZrB}_2$  powder (99.5% pure, Alfa Aesar, Germany) and different amounts (20, 30, 40, 50, 60 and 70 wt.%) of Cu powder (99.9% pure, Metal Powder Company, India) were dry mixed in a polyethylene bottle for 5 h and then the mixture was mixed with polyvinyl alcohol and compressed into 6.6 mm diameter and 5 mm thickness pellets by applying uniaxial pressure of 250 MPa. Polyvinyl alcohol was added as a binder during compaction, which was burnt off by slow heating the compacts at 500 °C. The pressureless sintering of the preheated pellet was carried out in a high temperature graphite furnace (Thermal Technology Inc., USA) at 1250 °C under a continuous flow of high purity argon gas (XL grade). After sintering a further homogenization was carried out at 1000 °C for 2 h in a tubular furnace under high purity argon gas. The sintered density was measured with an accuracy of  $\pm 1\%$  by liquid immersion technique using Archimedes principle. The Vickers hardness (load at 300 g and loading time 15 s) of different sintered samples and Cu bar was measured by a microhardness tester (LECO DM-400, Japan). These sintered pellets were fixed on one end of a Cu (99.9% pure) rod by adding a conductive Ag paste and baked for 10 h at 75 °C. This composite fixed with Cu rod was used as an electrode. A pure Cu rod (diameter, 6.6 mm) also used as another electrode for EDM (Electra, EMS 5535-R50ZNC, India) study. A mild steel plate (well polished) was used as workpiece material for EDM study. The tool and workpiece were kept as positive and negative electrode, respectively. Kerosene oil (fire point  $\sim 65$  °C) was used as dielectric fluid.

Initially the EDM with different  $\text{ZrB}_2$ –Cu composite was carried out under similar operating conditions (peak current 3 A, gap voltage 45 V, pulse on-time 30  $\mu\text{s}$  and dutyfactor 95%). A depth of cut of 0.2 mm was done on workpiece for each run. The MRR and TRR were measured for each run. The Cu electrode was also tested for the comparison study. Then the EDM study was carried out with different pulse on-time (peak current 3 A, gap voltage 45 V). The MRR and TRR of composites and Cu tool were measured at different pulse on-time and expressed in terms of weight loss per unit time (mg/min). The EDM was also done at varying peak currents with constant pulse on-time 30  $\mu\text{s}$ . The average surface roughness of machined workpiece and tool were also measured at different pulse on-time with the help of surface roughness measuring instrument (SURFCOM 120A, Carl Zeiss, Japan). The diametric overcut of the hole machined on workpiece was measured by tool maker microscope (Mitutoyo TM-101, USA). The machined surfaces were analysed by scanning electron microscope (SEM) (JEOL, JSM 840A, Japan). The phase changes on machined surface during the EDM was analysed by XRD technique using X-ray diffractometer (Philips PW 1840, The Netherlands).

## 3. Results and discussion

The relative density of composites is found to be 83.5, 86.5, 90.1, 90.5, 91 and 91.5% for 20, 30, 40, 50, 60 and 70 wt.% Cu addition, respectively. The relative density increases with the Cu addition due to decrease of porosity. The hardness of different  $\text{ZrB}_2$ –Cu composites is shown in Fig. 1. The maximum hardness is found at 30 wt.% Cu addition of  $\text{ZrB}_2$ –Cu composite. The Cu tool, which is used for comparison study having a hardness of  $97.5 \pm 2 \text{ kg/mm}^2$ .

The EDM studies on mild steel with  $\text{ZrB}_2$ –Cu composite as a tool material are shown in Figs. 2 and 3. Fig. 2 shows the MRR to increase from 20 to 30 wt.% Cu and reach a maximum at 40 wt.% Cu and then MRR is found to decrease with increase of Cu. The TRR (Fig. 3) increases rapidly from 30 to 40 wt.% Cu and then increases slowly with increase of Cu. By considering the higher MRR and reduced TRR between different electrodes,

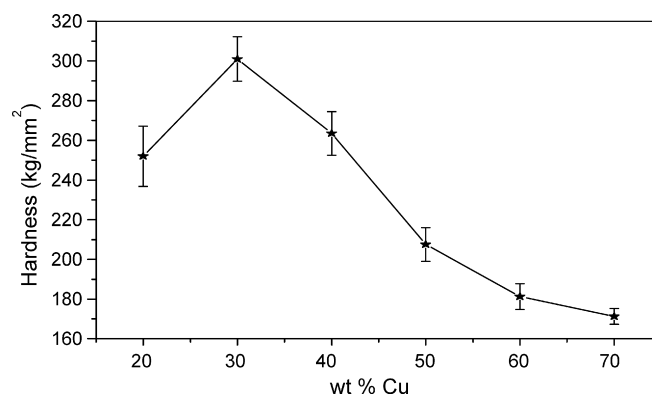


Fig. 1. Variation of hardness with Cu for  $\text{ZrB}_2$ –Cu composite.

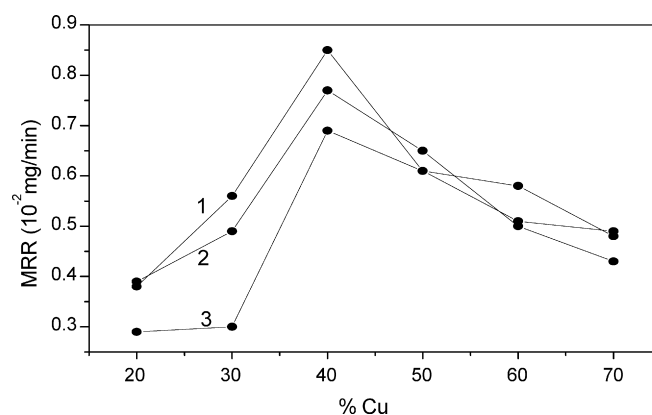


Fig. 2. Variation of MRR with different wt.% Cu at different runs (1–3).

the  $\text{ZrB}_2$ –40 wt.% Cu can be considered as best performed tool. This may be due to optimum combination of wear resistance, electrical and thermal conductivity at 40 wt.% Cu, which is the basic requirement of EDM tool. Hereafter the  $\text{ZrB}_2$ –40 wt.% Cu will be referred as A tool.

The MRR and TRR for A tool and Cu tool with different pulse on-time are shown in Fig. 4. The MRR and TRR are found to increase slowly up to 30  $\mu\text{s}$  pulse on-time and then increase rapidly for both cases. This is expected, which is due to more EDM energy input. Fig. 4 shows the MRR for A tool is higher with less tool wear than Cu tool. The less TRR of A tool indicates more wear resistance of A tool than Cu tool. Here the

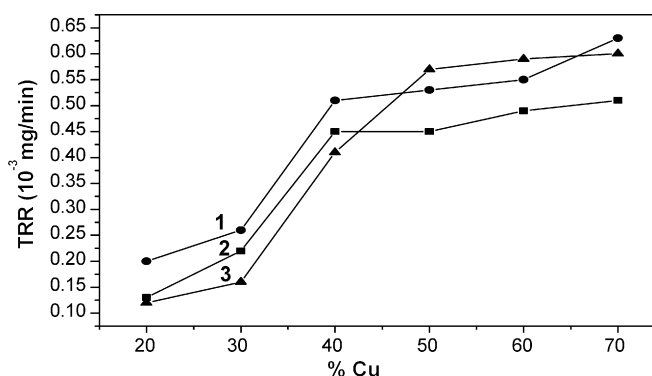


Fig. 3. Variation of TRR with different wt.% Cu tool at different runs (1–3).

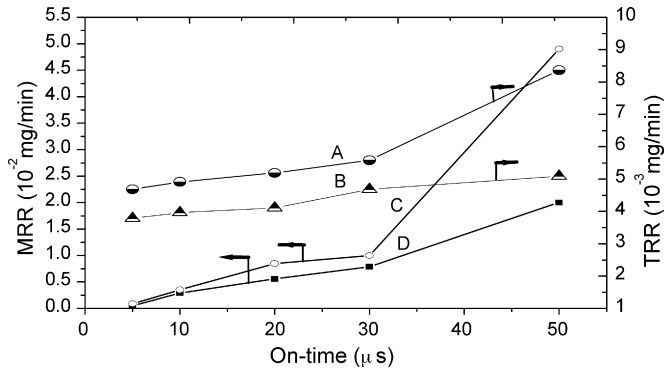


Fig. 4. Variation of MRR and TRR with pulse on-time: (A and B) TRR for Cu tool and A tool and (C and D) MRR of tool A, Cu, respectively.

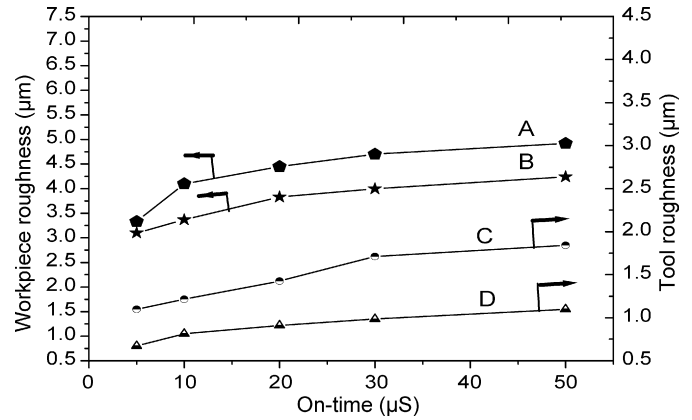


Fig. 6. Variation of average surface roughness of workpiece and tool with pulse on-time: (A and B) average roughness of workpiece for A tool, Cu tool and (C and D) roughness of A tool, Cu tool, respectively.

presence of  $\text{ZrB}_2$  particles increases the wear resistance of A tool. The high TRR of Cu tool is due to presence of more wear out material in the gap between the two electrodes, which results in decrease of MRR. That is why the MRR of A tool is more than Cu tool. The MRR and TRR with varying current of different tools are shown in Fig. 5. It shows more MRR with less TRR than Cu tool, which is similar to variation of MRR and TRR with pulse on-time. From Figs. 4 and 5 it is clear that the performance of composite tool is better than conventional Cu tool. The average surface roughness of workpiece and tool are found to increase with the pulse on-time (Fig. 6). This may be due to transmission of more EDM input energy, which causes to increase surface roughness. The resulting pyrolysis products, which accumulate on the machine surfaces are not entirely swept away by the flushing of dielectric and cause poor surface finish. The average roughness of workpiece and tool is found to more for A tool than Cu tool. The impression on workpiece is the mirror image of the tool. The diametral overcut of workpiece with different pulse on-time is shown in Fig. 7. It increases with the increase of pulse on-time, which is due to more input energy. When the pulse-on time increases, the affected area due to sparking or electron bombardment from the side-wall of the tool electrode increases and it leads to more overcut. The diametral overcut for Cu tool is found to be lesser than A tool. The high spark is responsible for more overcut for A tool. Again

the particle size of debris for A tool appears to be bigger than that of Cu tool, which increases the diametral overcut. Here the presence of hard  $\text{ZrB}_2$  particles in the debris in case of A tool may increase the diametral overcut. Again formation of another hard phase ( $\text{ZrC}$ ) on the tool surface is found during the EDM, which is confirmed from the XRD analysis. The details of which are discussed later. The presence of hard  $\text{ZrC}$  particle in the debris may increase of diametral overcut by impact action, which leads to more diametral overcut in case of A tool than Cu tool. The SEM micrographs of different tools after EDM (on-time, 50  $\mu\text{s}$ ) are shown (Fig. 8). The figure shows presence of agglomeration of fine particles over the surface. The pores (black spots in SEM photographs) are found to form on the tool surface, which is due to excessive wear of surfaces result from generation of high thermal stresses. The SEM/EDS analysis shows the presence of Cu, Zr, B, Fe and C on the tool surface (Fig. 9). Here the presence of carbon is not detected properly as EDS analysis cannot detect elements having low atomic number. The presence of Fe indicates that there is significant mass transport from workpiece to tool. Presence of a black layer is found on the tool surface after the machining, which is visible by naked eye. The black layer is nothing but a carbon

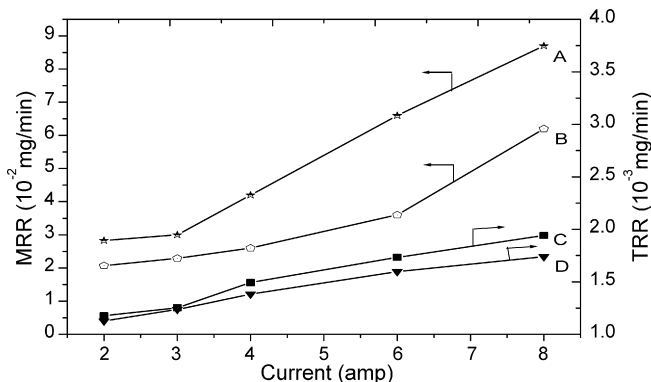


Fig. 5. Variation of MRR and TRR with current: (A and B) MRR for A tool, Cu and (C and D) TRR of Cu, A tool, respectively.

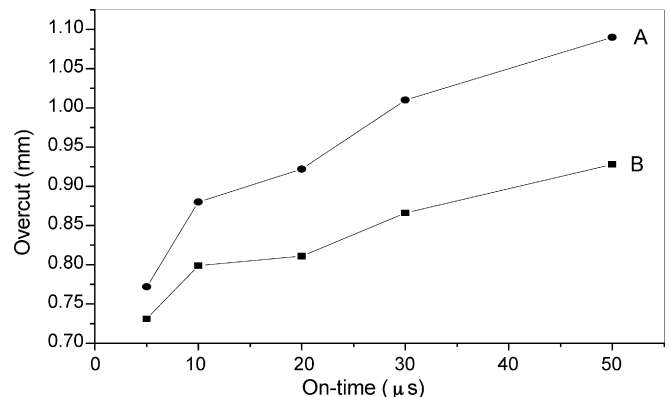


Fig. 7. Variation of diametral overcut with different pulse on-time: (A and B) for A tool and Cu tool, respectively.

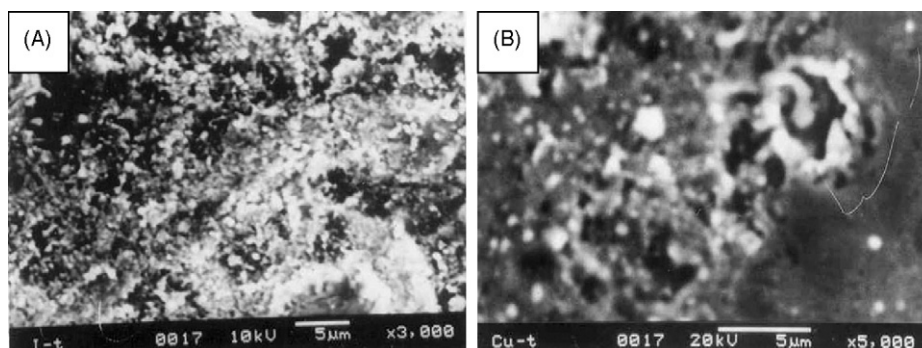


Fig. 8. SEM images of different tools: (A and B) A tool and Cu tool after EDM (pulse on-time 50  $\mu$ s), respectively.

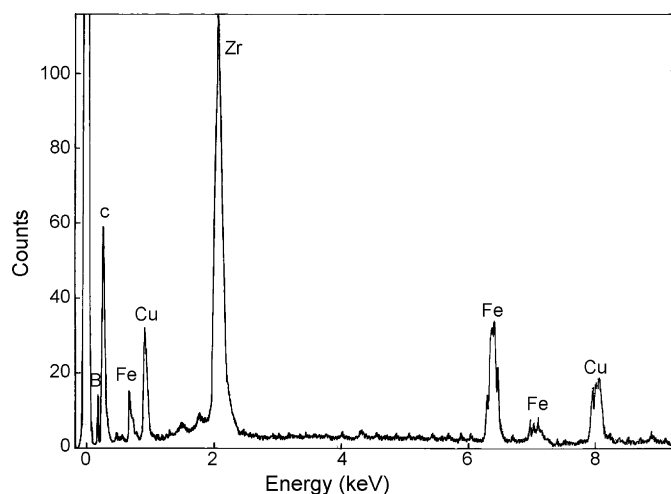


Fig. 9. EDS spectra of composite tool (after EDM).

layer, which is formed due to break down of dielectric during the EDM [9,10]. A similar type of layer is also found on workpiece surface. The MRR decreases due to presence of carbon upon prolonged machining. The machined surfaces of workpieces for different tools are shown in Fig. 10. One can observe the presence of solidification of molten phase on the surface during the EDM. The workpiece surface for A tool shows very severe melting as compared to that for Cu tool, which clearly indicates that the MRR for A tool is much more than Cu tool. The presence of fine particles is found on the machined sur-

faces. The SEM/EDS analysis on workpiece surface confirms the presence of Zr, B and Cu along with Fe. The presence of Zr, Cu and B indicates that the mass transport also takes place from the tool material to workpiece surface. During EDM the most of the wear out material from the machined surface is taken away by the dielectric media and remaining deposit on the surfaces. The XRD pattern of composite tool shows formation of ZrC as a new phase after EDM (Fig. 11). The high temperature generation during EDM may results partial dissociation of  $\text{ZrB}_2$  into Zr and B and then the Zr and C react to form ZrC. But no boron carbide formation is observed during the XRD study. The formation of ZrC on composite tool surface is observed in present study, which may increase the wear resistance of composite, leading to reduced TRR of A tool. No phase changes are found on Cu tool surface and only peak intensity is found to change after EDM (Fig. 12). The plane (1 1 1) is the highest intensity plane (JCPDS file-040836) before EDM but after EDM the plane (2 0 0) becomes the major intensity plane. This may be due to development of preferred orientation due to heat effect on surface. The presence of retained austenite is observed at the workpiece surface after the EDM (Fig. 13). This is due to the ferrite transformation into austenite and reverse transformation during cooling. The formation of iron carbide is not found in the present study. It is reported that the formation of several carbides like  $\text{Fe}_3\text{C}$ ,  $\text{Fe}_{2.4}\text{C}$ , etc., are found in case of EDM of high carbon steels at very high energy input [11,12]. In the present study, an extra jet of dielectric fluid is inserted in the gap between two electrodes, which takes away the carbon deposition. This leads

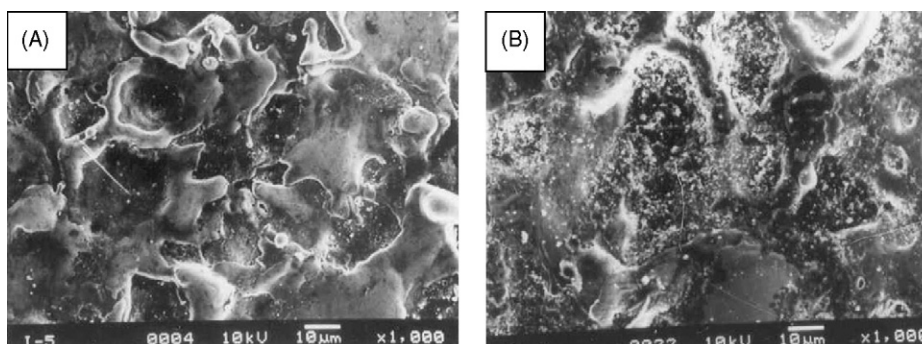


Fig. 10. SEM images of machined surface (pulse on-time 50  $\mu$ s): (A and B) for A tool and Cu tool, respectively.

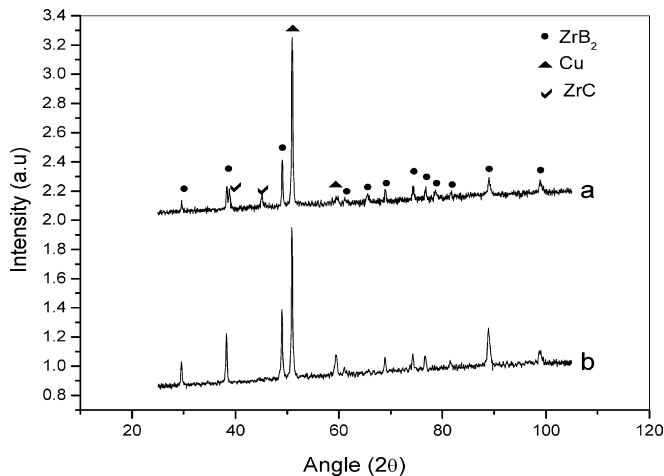


Fig. 11. XRD patterns of composite tool: (a) after EDM and (b) before EDM.

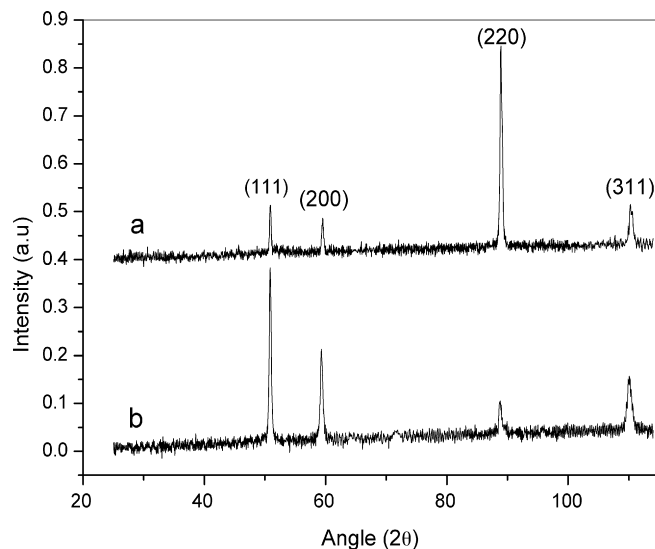


Fig. 12. XRD patterns of Cu tool: (a) after EDM and (b) before EDM.

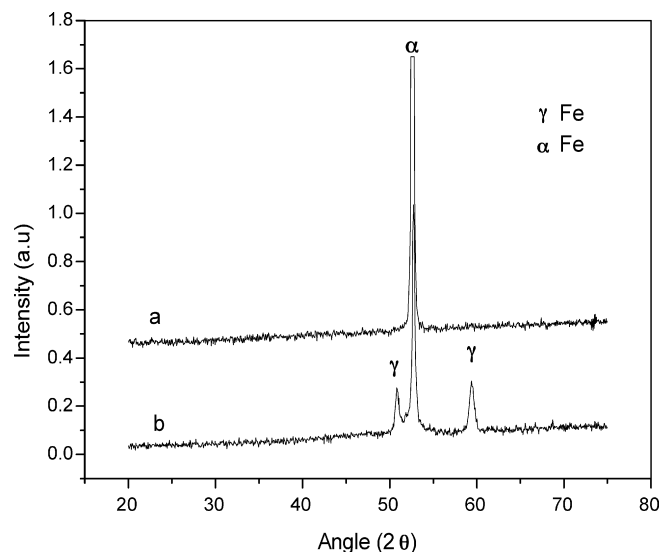


Fig. 13. XRD patterns of workpiece: (a) before EDM and (b) after EDM.

to negligible reaction between Fe and C, which is not detected by XRD study.

#### 4. Conclusions

The ZrB<sub>2</sub>–Cu composite tool has been developed for EDM study. The conclusions based on the various experimental results are summarized below.

The ZrB<sub>2</sub>–40 wt.% Cu composite tool shows higher MRR with decrease TRR over pure Cu tool. The average surface roughness of tool surfaces and diametral overcut produced on the workpiece are found to be more for ZrB<sub>2</sub>–40 wt.% Cu composite tool than Cu tool. The machined surface of tool shows presence of agglomeration of fine particle, porosity, etc. There is significant amount of mass transport between the electrodes during the EDM. The ZrC is formed on the composite tool surface while retained austenite is observed on the workpiece surface. The Cu tool surface shows development of preferred orientation during the EDM. The present research work can give some new information to the manufacturing industry.

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